INTEGRATED NATIONAL ASSESSMENT OF HARMFUL ALGAL BLOOMS

EXECUTIVE SUMMARY

INTRODUCTION

Harmful algal bloom (HAB) events are common nationwide. Blooms of familiar and previously unknown species have occurred in new coastal areas and HABs are now found throughout the US coastal area, from the Gulf of Maine through the Gulf of Mexico and north to Alaska. HAB events regularly threaten coastal living resources, restrict local harvests of fish and shellfish, divert public funds to monitoring programs, burden medical facilities, and depress local recreational and service industries.

What are harmful algal blooms and how do they occur?

Among the thousands of species of microscopic algae at the base of the marine food chain are a few dozen that produce toxins. Some of these toxic species make their presence known sometimes as a massive “bloom” of cells that may discolor the water. Other species, in dilute, inconspicuous concentrations of cells, are noticed because they produce highly potent toxins that either kill marine organisms directly, or transfer through the food chain, causing harm at multiple levels.

Blooms of toxic algae were commonly called “red tides,” since, in the case of some dinoflagellates, the tiny organisms may increase in abundance until they dominate the planktonic community and tint the water reddish with their pigments. Because other blooms may tint the water bright green or adverse effects can occur when algal concentrations are low and the water is clear, the scientific community now uses the term “harmful algal bloom” or HAB. This descriptor applies not only to toxic microscopic algae but also to nontoxic macroalgae (seaweeds) which can grow out of control and cause ecological impacts.

Some dinoflagellate and cyanobacteria species produce resting stages, (called “cysts” and “akinetes,” respectively) that allow the organisms to survive unfavorable or stressful local conditions (e.g. water temperatures that are too cold, light levels that are too low). These resting stages sink to the bottom and lie dormant on the ocean floor until more favorable growth conditions return. If undisturbed by natural forces, a cyst can stay in this state for weeks, months, even years. The return of favorable conditions stimulates the cyst to germinate; . the cyst breaks open and a swimming cell emerges. This cell reproduces through simple division within a few days of “hatching.” If conditions remain favorable, the cell will continue to divide, multiplying exponentially (from 2 to 4 to 16, etc.). A single cell multiplying in this way can produce 5000 to 8000 cells within a week.

What are the Impacts of Harmful Algal Blooms?

HAB impacts include human illness and death from ingesting contaminated shellfish or fish, mass mortalities of wild and farmed fish, mortalities of marine mammals, sea turtles, seabirds,and other protected species, and alterations of marine food chains through adverse effects on eggs, young, and adult marine organisms.

Exposure to toxins. Impacts from some HABs occur when marine fauna are killed by algal species that release toxins and other compounds into the water. Humans can also become ill from direct exposure to biotoxins. In addition to causing NSP, brevetoxin (the biotoxin produced by the dinoflagellate *Gymnodinium breve*) can become aerosolized and is a respiratory irritant when inhaled. *Pfiesteria piscicida* produces as yet unidentified toxins that have been implicated in temporary short-term losses of neurocognitive abilities (short-term memory) in people exposed to waters or aerosols containing some as yet unidentified toxin or bioactive compound.

Shellfish poisoning syndromes. When toxic algae are filtered from the water as food by shellfish such as clams, mussels, oysters, and scallops, these toxins accumulate in the shellfish tissues.[1,2] Typically, the shellfish themselves are only marginally affected. However, a single clam can sometimes accumulate sufficient toxin to kill a human or large marine mammal. Shellfish poisoning syndromes have been given the names paralytic (PSP), diarrhetic (DSP), neurotoxic (NSP), and amnesic (ASP) on the basis of descriptive human symptoms. These syndromes have severe effects, some of which are fatal. All are caused by biotoxins synthesized by marine dinoflagellate except for ASP which is produced by diatoms.

Other HAB impacts. Some HABs can kill fish without toxins by physically damaging gills or by creating low oxygen conditions. Large, prolonged blooms alter the distribution of light, leading to decreasing densities of valuable submerged aquatic vegetation in our coastal areas and degrading nursery habitats.[3] These impacts can result in long-term damage to local shellfish and aquaculture fish stocks, sometimes leading to collapse of fisheries.

STATUS OF HARMFUL ALGAL BLOOMS IN US WATERS

Paralytic Shellfish Poisoning

Paralytic Shellfish Poisoning (PSP) is a worldwide problem that affects more US coastline than any other HAB impact.[4] PSP is caused by several closely related species of dinoflagellates in the genus *Alexandrium* and is a major problem in the northeastern and northwestern United States. The affected resources are predominantly shellfish, but PSP toxins, called saxotoxins, also affect higher levels of the food web, including lobsters, fish, and marine mammals.[5, 6] Saxotoxins are accumulated by filter-feeding shellfish and other grazers and are passed on to humans and other animals, leading to illness, incapacitation, and even death. There is no antidote and health risks are controlled primarily through monitoring the shellfish and rapidly closing affected regions to harvest once toxins are detected.

Northwest. Early European explorers and coastal Native American tribes of the West Coast reported illness and mortalities from eating shellfish over 200 years ago.[7, 8] In 1793, two members of Capt. George Vancouver's crew died from PSP during their exploration of the waters around Vancouver Island. In 1799, more than 100 Aleut died of PSP in what is now Alaska. In 1942, PSP resulted in the deaths of three people as well as mass mortalities of seabirds.[9] Since then, the Washington coast from Dungeness Spit on the Strait of Juan de Fuca to the mouth of the Columbia River has been closed to bivalve harvesting each year from 1 April through 31 October. From 1962 to 1989, there were toxic events most years along the California coast.[10] Most toxic events occurred between May and October with toxin levels typically highest in July and August. In 1917, five million pounds of shellfish products were harvested from Alaskan waters, but today the state's commercial bivalve industry is virtually nonexistent. PSP is so widespread in Alaska that all beaches and waters are closed to recreational shellfish harvesting; commercial harvesting is very limited and strictly controlled. The destruction of the clam industry, estimated at 25-50 million pounds of bivalves (blue mussels, butter, little necks, and horse clams, geoduck, oysters, and cockles) per year, is in large part a result of product contamination by PSP.[11] Other commercially valuable species, such as Dungeness crabs, are also affected by PSP, presumably from consumption of tainted bivalves.

Northeast. PSP has been a recurring phenomenon in large areas of the northeastern United States every year for over two decades. Prior to 1972, shellfish toxicity was known only in eastern Maine. That year, a massive bloom introduced Alexandrium tamarense to southern waters, and now the entire New England coastline experiences periodic PSP outbreaks with extensive shellfish bed closures and economic losses. Although blooms have not occurred in all regions, the detection of A. tamarense cells and cysts (the dormant stage) in small embayments in Connecticut and Long Island as far south as New Jersey suggest a gradual southward dispersal of toxic Alexandrium species over the last several decades. [12-14]

In 1998:

Six people were made ill, one was hospitalized, in Seattle after eating PSP-contaminated mussels harvested from south Puget Sound. PSP contamination closed significant areas to both recreational and commercial harvesting. In separate incidents, two people in Alaska experienced mild symptoms of PSP after consuming what were believed to be contaminated butterclams and limpets. High levels of PSP toxins were detected at an oyster farm on the northern coast of Chicagof Island and in Little Duncan Bay on Kupreanof Island in southeast Alaska, closing the entire harvest area around Kodiak Island. The closure of Kachemak Bay East to commercial butterclam harvesting, which began in 1997, continued through 1998.[15]

In New England, blooms of Alexandrium were responsible for the closures of shellfish beds in Southern Maine, New Hampshire, and Northern Massachusetts from mid-May to June. Toxicity in salt ponds on Cape Cod resulted in brief closures in May. The surf clam beds on Georges Bank continued to be closed due to residual toxicity from bloom events that occurred in 1990.[16]

Neurotoxic Shellfish Poisoning

The toxic dinoflagellate *Gymnodinium breve* forms red tides in waters from the Gulf of Mexico (Mexico-Florida) to the South Atlantic Bight (off the Southeastern United States). This species produces neurotoxins (called brevetoxins) and hemolytic substances that can harm human and marine mammal populations. When humans eat shellfish that have fed on *G. breve*, they may suffer severe gastrointestinal and neurological symptoms associated with Neurotoxic Shellfish Poisoning (NSP). While there is no antidote for NSP, full recovery usually occurs within several days. The neurotoxins and hemolytic substances produced by *G. breve* can also cause human respiratory irritation.

Blooms are usually seasonal, starting in late summer/fall and lasting three to four months in duration. Extensive blooms can cover large areas of water as much as 30,000 km and persist for up to eighteen months. Bloom events significantly impact fishing and tourist industries and alter population levels or recruitment potential of affected marine animals.[17, 18]

Toxic blooms of *G. breve* are generally identified by visual confirmation (water discoloration and fish kills), illnesses in people consuming contaminated shellfish, and human respiratory ailments.[19-21] Other detection strategies include time-intensive chemical analyses which can assay for the presence of the brevetoxins within shellfish tissue samples [22, 23] and mouse bioassays.[24] Effective monitoring programs have prevented most human exposure except when blooms take place in previously unaffected areas that were not being monitored. [25] Recent technological advances, such as remote-sensing methods, increase detection and bloom characterization capabilities.[26-33] Computer-based instrumentation has enabled the use of bio-optical techniques for identifying and characterizing harmful algal blooms in general. [34]

Amnesic Shellfish Poisoning

ASP, so named because one of its most severe symptoms is the permanent loss of short-term memory, can be fatal. The ASP toxin, domoic acid, is produced by diatoms in the genus *Pseudo-nitzschia* that, until recently, were thought to be free of toxins and harmless. Domoic acid poisoning (DAP), associated with ASP in humans, was discovered in 1987 when more than one hundred people became ill and three died from eating contaminated mussels harvested on Prince Edward Island. ASP became a concern along the west coast of North America in September, 1991 when more than one hundred brown pelicans and cormorants were found dead or suffering from unusual neurological symptoms in Monterey Bay, CA.[35-37] This event was attributed to a bloom of *Pseudo-nitzschia australis*.[38, 39] Scientists have since learned that domoic acid, like many other biotoxins, can accumulate in the tissues of fish and crabs.

In 1998:
The now common *Pseudo-nitzschia* blooms off the California coast revealed disturbing new consequences when the first known case of domoic acid's involvement in marine mammal deaths were confirmed. More than fifty sea lions, most of them pregnant females or young adults, died along the California coast from San Luis Obispo to Santa Cruz. (Sea lions eat anchovies and sardines which can accumulate domoic acid). Washington experienced the highest domoic acid levels ever detected off that coast. Levels of 286 ppm were detected in razor clams.[15] Since razor clams have been known to take 9-12 months or more to depurate (flush out) domoic acid, continued toxicity may keep the shellfishery closed through 1999.[16] Oregon also reported record levels of domoic acid off the coast in 1998. All coastal beaches were closed for the month of July due to elevated levels of PSP toxins. The state's northern beaches and ocean spits were closed to recreational and commercial shellfish harvesting late July through August.[15]

Pfiesteria piscicida and related species

In 1991, *Pfiesteria piscicida*, an ichthyotoxic dinoflagellate with "ambush predator" behavior and a complex life cycle, was found at a fish kill in the Pamlico River, a large estuary in North Carolina.[40, 41] Since then, fish kills attributed to this organism have become an almost yearly event in North Carolina, killing an estimated 1 billion fish over the last decade. In 1997, toxic *P. piscicida* was found to be the cause of fish kills in three tributaries on Maryland's eastern shore. *P. piscicida*, which is one of several newly-discovered species of "phantom" dinoflagellates, has an extremely complex life cycle which makes it difficult to detect and study. Laboratory studies suggest that *P. piscicida* is stimulated to transform from benthic cysts, amoebae, or non-toxic flagellated stages to icthyotoxic (fish-killing) zoospores by some unknown substances freshly secreted by finfish and shellfish.[41] *P. piscicida* has been known to affect human health, and fisheries in mid Atlantic and southeastern estuaries. In the laboratory, human exposure to aerosols from toxic cultures has been linked to short-term neurotoxic symptoms. Fishermen and others exposed to estuarine waters where outbreaks have occurred have also complained of similar problems.

Pfiesteria-like organisms (PLOs) are dinoflagellates that are morphologically and genetically similar to *P. piscicida.* As such they can easily be confused with *P. piscicida* under a light microscope. They can be separated out using scanning electron microscopy (SEM) to identify their external plate patterns or by using molecular probes. Since they can co-occur with *P. piscicida* in the same habitat and may have similar niches, they can be present during fish kills and fish lesion events. Whether they produce neurotoxins or bioactive compounds that can also be icthyotoxic, has not been demonstrated. Most PLOs are new species, yet to be described scientifically. Several PLOs are known as "cryptoperidiniopsoids" due to the "cryptic" configuration of their outer plates. Cryptoperidiniopsoids have been identified from Florida, Maryland, and North Carolina waters in areas where fish disease events have occur. In Florida, they occur where *P. piscicida* has not been found. It is unclear what role PLOs may play in fish disease or fish kill events, but studies are underway to clarify their involvement in such events.

Ciguatera Fish Poisoning

Ciguatera fish poisoning (CFP) is a malady associated with dinoflagellate toxins that accumulate in the flesh of tropical fish. CFP toxins (ciguatoxins) are produced primarily by epiphytic dinoflagellates (*Gamberdiscus toxicus, Amphidinium carterae, Coolia monotis*, and several in the genera *Prorocentrum, Ostreopsis*, and *Thecadinum*) which grow on the surface of red and brown macroalgae in virtually all sub-tropical to tropical US waters. Ciguatoxins accumulate in fish tissues and persists over extended periods; if consumed by humans, it causes long-term, non-lethal but debilitating illness.[42, 43] CFP is the most frequently reported non-bacterial illness associated with eating fish in the United States and its territories. Southern Florida, Puerto Rico and the Hawaiian islands, account for the majority of documented CFP incidents in the US and it is estimated that nearly 50% of the adults in the US Virgin Islands have been poisoned at least once. The actual number of CFP cases is estimated to be 2- to 5-fold higher than reported, since there is no confirmatory laboratory test and reporting to the US Centers for Disease Control and Prevention is voluntary. CFP was once restricted to the tropical coastal areas of the US but reports of CFP intoxications from temperate “inland” locations have been increasing as a result of the widespread commercial distribution of sub-tropical and tropical fish. Presently, no coordinated, systematic monitoring programs exist for CFP in the US and its territories.

Brown Tide Blooms

Blooms of the small golden brown algae *Aureococcus anophagefferens*, referred to as “brown tide” due to the resulting water color, have been confirmed in many locations along the northeast coast of the United States, especially in Narragansett Bay, RI, Barnegat Bay, NJ, and the Peconics-Gardiners Bay estuary and south shores of Long Island, NY.[44] Brown tide algal have also been detected in aquatic systems ranging from Massachusetts to Virginia, but include many areas with no previous history of visible or destructive blooms.[45]

Brown tides blooms (BTBs) occur in shallow, mixed waters, and take place during late spring and summer. A bloom event can persist for as long as one to four months. The high density of algae growing during a bloom causes reduced penetration of light into the water, which is detrimental to the survival of eelgrass which provides a critical nursery habitat for numerous fish and shellfish.[46, 47] Zooplankton and larval fish do not eat brown tide algae, but suffer increased mortality when the algal cell density rises to a threshold level. Eggs of important estuarine fish species, such as red and black drum and spotted seatrout, have reduced hatching and the young larvae rapidly die from lack of food. BTBs also cause mortality, recruitment failure and growth inhibition of numerous commercially important bivalves, including blue mussels in Rhode Island,[48] and bay scallops in New York.[49]

Northeast. The first northeastern outbreaks of BTBs occurred concurrently in New York and Rhode Island in 1985, and blooms have occurred in NY bays ever since. Brown tides have adverse affects on plant and animal life in the affected areas. The initial notable impact of brown tides in the mid-1980s were on the eelgrass and bay scallops in Long Island bays[46, 48, 50] and mussels in Narragansett Bay.

Texas. The brown tide species *Aureoumbra laguensis* first created an extensive bloom in Laguna Madre, Texas, in 1990, and has bloomed every year since. The blooms have had substantial ecological impacts including decreased light penetration levels, loss of seagrass beds, and reduced zooplankton grazing rates.[51, 52] Recent investigations have inquired as to whether the hypersaline conditions in the Laguna Madre are selecting for *A. laguensis*, which may have an adaptive tolerance to such extreme conditions.[53] It is possible that significant ecosystem changes will result from the long-term dominance of the Laguna Madre system by these brown tide blooms.

In 1998:

From late April to early July, BTBs were present in the southern bays of Long Island, NY (Great South Bay, West Neck Bay). As in the past, these blooms impacted scallops, hard clams, and mussels, and shaded submerged aquatic vegetation. They also created negative aesthetic effects such as water discoloration and reduced light penetration. Barnegat Bay, NJ and the southern back bay lagoons experienced brown tide blooms from May to June. Bloom episodes from May to July off the northern Monmouth County coast resulted in bottom hypoxia (low oxygen levels) in the late summer.[16]

Harmful Cyanobacterial Blooms

Harmful cyanobacterial blooms (HCBs), common to freshwater systems throughout the world, are often associated with excessive nutrient loading in oligohaline (low-salinity) aquatic systems. Excessive growths of *Anabaena, Aphanizomenon, and Microcystis* species can lead to harmful HCBs that can cause severe neuro-, cyto- and hepatotoxicity in humans, farm animals, birds, fish and invertebrates. HCBs have occurred in large estuarine systems (e.g., Chesapeake Bay, Albemarle-Pamlico Sound and Florida Bay) and freshwater systems such as the Great Lakes. A persistent algal bloom, dominated by the HCB species *Synechococcus elongatus*, appeared in 1991 in mid-north central Florida Bay. It spread to central and western areas, and persists to this day. This HCB, and the resultant turbid waters and reduced light penetration, have been implicated in large-scale mortalities of seagrass and sponge beds and even the degradation of Florida Keys coral reefs. Large blooms of the HCB species *Microcystis* occurred in Lake Erie during the summers in the mid and late 1990s, despite the recent improvements in the lake's water quality. Preliminary evidence suggest that these blooms are related to the infestation of zebra mussels and resultant changes in grazing loss rates and/or nutrient ratios. HCB blooms often terminate rapidly or "crash" in response to sudden physical perturbations (e.g., rapid drop in temperature, sudden destratification and water column turnover, or reduced irradiance associated with poor weather). When crashes occur, excessive oxygen consumption that occurs as the biomass decays can lead to anoxia (no oxygen). This chain of events has been responsible for major estuarine fish and shellfish kills and loss of habitat for benthic infauna.[54, 55]

Macroalgae

Macroalgae (seaweeds) cause problems throughout the coastal waters of the United States. Over the past several decades blooms of macroalgae have been increasing along many of the world's developed coastlines in response to nutrient enrichment associated with coastal eutrophication. Macroalgal blooms occur in nutrient-enriched estuaries and nearshore areas which are shallow enough for light to penetrate to the sea floor. Macroalgal blooms are unlike "typical" phytoplankton HABs because they lack direct chemical toxicity, have a broader range of ecological effects, and last longer. However, thsee macroalgal blooms can have significant negative effects, pervasively and fundamentally altering coastal ecosystems.[56]

Once they are established, macroalgal blooms may remain in an environment for years to decades until the nutrient supply decreases. This is in contrast to phytoplankton blooms that are usually relatively short-lived (days to weeks). Macroalgal blooms can be particularly harmful to coral reefs, which are fragile, highly diverse ecosystems that are adapted to stable, oligotrophic (low nutrient) conditions. Under high nutrient conditions, opportunistic macroalgal species outcompete, overgrow, and replace coral reefs. Studies of coral reefs from around the Caribbean[57-63] and around the world[64-68] have confirmed the link between nutrient enrichment and increased dominance of reefs by macroalgae. Seagrass ecosystems can also be disrupted and destroyed by macroalgal blooms. Macroalgal blooms in South Florida have contributed to the marked decline in extent and vigor of coral reef and seagrass ecosystems that provide a vital nursery habitat for pink shrimp, spiny lobster, and many species of finfish.

Diarrhetic Shellfish Poisoning

Diarrhetic Shellfish Poisoning (DSP) is currently not a problem in the United States. However, it is considered by some scientists to be the most common and globally widespread phytoplankton-related seafood illness. DSP-producing species of phytoplankton such as *Dinophysis acuminata* and *Prorocentrum lima* occur throughout all United States temperate coastal waters. The first confirmed incidence of DSP in North America occurred in 1990 and 1992 in Canada. DSP, attributable to *P.*

lima, has been reported on occasion from northern Maine and from Georges Bank.

HAB Fish Kills

Catastrophic losses of cultured and wild fish not only occur from many toxic algal species, but also from others that do not cause illnesses in humans. Blooms of the diatom, *Chaetoceros convolutus*, do not produce a toxin but have caused massive fish kills. Chains of these cells armed with long setae and short secondary spines become lodged in fish gills and cause irritation and eventually suffocation as a result of mucous production. *Chaetoceros convolutus* and *Chaetoceros concavicornis* have been repeatedly implicated in the death of pen-reared salmon, especially in the Pacific Northwest.

Blooms of the golden-brown alga, *Heterosigma akashiwo*, have been associated with extensive mortalities of farmed fish in US and Canadian waters of the Pacific Northwest. In 1986, blooms of *H. akashiwo* were responsible for the loss $2.5 million of farmed salmon (about 1/3 of the population) in Sechelt Inlet, BC, and in 1989, Washington State and Canada each lost $4 million of penned salmon from such blooms. Since then, commercial salmon aquaculturists in both countries have experienced substantial economic losses from these blooms. *H. akashiwo* has recently been linked to mortalities of salmon in the wild.

TRENDS OF HARMFUL ALGAL BLOOM EVENTS

There are very few areas of US coastal waters that are unaffected by HABs. One question that scientists ponder is “Are HABs spreading and is the problem getting worse?” A growing body of evidence suggests that HABs are increasing around the globe.

Maps of the expansion of HABs in the US indicate the scale of the problem now compared to 25 years ago. We have more toxic algal species, more algal toxins, more areas affected, more fisheries resources affected, and higher economic losses.

Why is this? The are many reasons. The first thought of many is that pollution or other human activities are involved. On close inspection, however, many of the “new” or expanded HAB problems in the US occurred in waters where pollution is not an obvious factor. The organisms responsible for HABs have been on earth for a long time, so new bloom events may simply reflect better detection methods and more observers rather than new species introductions or dispersal events. The 1987 NSP event in North Carolina is a good example, as that was a Florida bloom carried by the Gulf Stream to North Carolina waters - a totally natural phenomenon with no linkage to human activities. Likewise, a massive 1972 red tide was responsible for introducing dormant cysts of the PSP-producing species Alexandrium tamarense to southern New England waters, where it has persisted to this day. Those coastal waters have seen an increase in pollution over the years, but the actual introduction and colonization of the species is the result of natural currents and environmental forcings, including a hurricane that occurred immediately prior to the 1972 bloom. It may be that subsequent blooms of this species are enhanced by pollution, but this has not yet been demonstrated. The appearance of ASP along the West Coast after 1991 is also not a result of pollution, but rather to communication among scientists and improved chemical detection methods that led to the identification of a toxin that was surely present in those waters for many years. Some believe that humans may have contributed to the spreading problem by transporting toxic species in ship ballast water, but this also remains an unproven hypothesis in the United States with respect to HAB species. Another causative factor is that we have dramatically increased aquaculture activities that have led to increased monitoring of product quality and safety. This monitoring may be revealing indigenous toxic algae that were probably always there.

The linkage to pollution should not be ignored, however, as the increase of nutrient inputs into our coastal waters will stimulate “background” populations of microscopic and macroscopic algae (seaweeds) by fertilizing them into bloom proportions. Harmful or toxic species will thus be more abundant and more noticeable. Some scientists even argue that the nutrients that humans supply to coastal waters are delivered in proportions which differ from those that naturally occur, such that we then alter the species composition of the algae by favoring certain groups better adapted to our nutrient supply ratios. Among the favored groups are some HAB species. One example where nutrient inputs have been linked to harmful blooms is with the ambush predator dinoflagellate Pfiesteria. That organism, and many closely related fish-killing species, seems to thrive in polluted waters.

One way to view the expansion of HAB phenomena in the U.S. is that we are better defining the boundaries of the problem - boundaries that may be expanding somewhat due to pollution or other global change issues, but which were always bigger than we thought. As we identify new toxins and new toxic species, we begin to see the nature and extent of the problem as it always was. This does not negate our concern about the expansion at all, nor does it alter the manner in which we must mobilize resources to attack it. The national and global HAB problem is serious and large - much larger than we thought. If it is also growing due to human activities, then our concerns are even more urgent.

The maps showing the change in the HAB events since 1972 are useful, but they give no information about the frequency of the events. A single outbreak will look the same as an annually recurrent bloom. A series of maps has thus been generated which depict the frequency of specific HAB problems along the U.S. coast over the last 10 years. These charts will be updated on an annual basis allowing a time series of the events to emerge.

PUBLIC HEALTH IMPACTS

The increasing frequency, intensity, and distribution of HAB events increases the likelihood that people will become ill from exposure to these toxins, and their presence has implications not only for public health, but also for nutrition, medical care, resource development, and tourism.

Human illnesses caused by marine seafood toxins have been recognized for over 200 years. The accumulation of algal toxins in seafood can cause neurotoxic, paralytic, amnesic, and diarrhetic shellfish poisoning as well as ciguatera fish poisoning.[69] Most are acute illnesses with symptoms lasting a few days (NSP, DSP). PSP induces temporary paralysis that can be fatal if respiratory support is not provided. ASP can result in chronic amnesia or dementia, and ciguatera fish poisoning can result in chronic peripheral neuropathies. Ciguatera fish poisoning is the most common food-borne illness caused by a chemical toxin and accounts for more than half the food poisonings associated with fish in the US.[70] These algal toxins are a serious threat to human health because they are not destroyed by cooking or storage (e.g., freezing, drying or salting) and there are no antidotes.

Historically, marine seafood poisonings were limited to geographic areas where specific algae and host organisms (clams, mussels, reef fishes) thrived (i.e. temperate to tropical coastlines and coral reefs). Given the global distribution of marine seafood products, the growth of aquaculture, tourism, and increased frequency of HABs, most of the world's population could potentially be at risk for these diseases.

Epidemiologic data on marine seafood toxin syndromes primarily comprise case reports and case series presented in the scientific literature or popular press, or present as part of local history. Seafood poisonings are not likely to be recognized by physicians outside of areas where poisonings have historically occurred, and poisonings are not likely to be reported to physicians in areas where the disease is endemic (e.g., ciguatera fish poisoning in Hawaii). Thus, it is likely that documented cases of illness from marine seafood toxins represent less than the "tip of the iceberg."

Other health effects from environmental exposure to toxins produced by marine microorganisms may be equally important in terms of public health impact. For example, there are anecdotal reports from Florida and Texas of elderly people, asthmatics, and otherwise healthy adults experiencing eye and nose irritation and respiratory distress during red tide events. The extent of health effects from environmental exposures to toxins aerosolized during HAB events are currently undocumented.

HABs with potential environmental human health impacts are also found in fresh and brackish water. Cyanobacteria produce potent neuro- and hepatotoxins, and extensive blooms occur in the source waters for some public drinking water systems, particularly in Florida. A 1996 outbreak of renal and hepatic failure in Brazil was associated with a freshwater cyanobacterial bloom that contaminated the water supply of a dialysis clinic. This outbreak suggests that at least some current treatment technologies may not effectively remove algal toxins from drinking water.

HABs also comprise an emerging issue in environmental health. Unknown and newly identified microorganisms may produce toxins harmful to freshwater and marine life and to people. For example, Pfiesteria piscicida is a dinoflagellate that was identified and characterized in 1996.[71] This organism has been found in estuarine waters in Maryland and North Carolina in association with fish disease and fish kill events. Laboratory workers working with cultures of these organisms reported a number of health problems, including respiratory irritation and problems with concentration and memory. There is concern that people may become ill following environmental exposure to *Pfiesteria piscicida*, similar organisms, or any toxins they produce. A recent report suggested that people experience learning and memory difficulties following exposure to waterways that contain *Pfiesteria piscicida.*[72] However, the toxins produced by this organism have not been identified and characterized; thus, there is no biological marker of exposure, and it is currently not possible to verify environmental exposures to either the organism or its toxins. Current epidemiologic research may provide additional information regarding the association between environmental exposure to these organisms and subsequent human health outcomes.

Given the large-scale under-reporting, the apparent increase in the incidence and geographic distribution of HABs, and evidence that the public health impacts of HABs are not limited to food poisonings, there is an urgent need for multi-faceted public health action, particularly in the areas of disease surveillance, health care provider education, epidemiologic studies, and emerging issues.

ENVIRONMENTAL IMPACTS

The environmental impacts of HABs range from subtle to the dramatic, from the invisible effects on microscopic plankton organisms to the deaths of the world's largest animals. Although deaths of endangered marine animals often focus public attention on these harmful algal species, all of the consequences of HABs presented here impact coastal productivity and the healthy coastal areas that the public desires for commerce, recreation, sport, settlement, and tourism.

Many bird and mammal species may be affected by algal toxins. There have been a number of documented occurrences of HAB-related mortality in marine and freshwater aquatic species and some of these die-offs have involved substantial numbers of animals. Domoic acid poisoning caused mortality in brown pelicans and Brandt's cormorants as well as sea lions on the central California coast and is recently suspected to be affecting southern sea otters.[73] Brevetoxin has been documented as the cause of mortality in manatees and suspected as the cause of mortality in lesser scaup and other bird species on the Gulf Coast for a number of years.[74, 75] Saxitoxin has been strongly suspected as the cause of mortality in sea birds (common terns, shags, great cormorants, northern fulmars, herring gulls, common murres, Pacific loons, and sooty shearwaters).[76-78] Cyanobacterial toxicosis has been suspected in mortalities of free-ranging ducks, geese, eared grebes, gulls, and songbirds.[79, 80]

There have been many reports of suspected HAB-associated mortality in wildlife, but in most instances the role of algae as the primary cause of a mortality event is presumptive rather than definitive. For instance, if a wildlife die-off occurs in conjunction with a noticeable algal bloom, the bloom is often implicated as the cause of the mortality event without additional proof. Conversely, because of the ephemeral nature of some HABs it may be difficult to make the connection between a bloom and a die-off event. Little is known about the pathogenicity of algal toxins in fish and wildlife, including the induced physiologic changes, toxic exposure levels, and subacute or chronic effects. In addition, field signs of illness or tissue lesions caused by HABs are not well known or described for wildlife species. Since there are generally not good baselines for comparison or laboratory studies that have established concentrations of toxins required to produce sickness or death in wildlife species, even when levels of particular toxins can be measured in animals from mass mortality events, it may be difficult to assess their significance. Exposure to sublethal levels of toxin may lower productivity, decrease resistance to other diseases, and alter an animal's behavior thereby predisposing it to predation; little work has been done to document the effects of acute or chronic exposure of algal toxins on wildlife species. In addition to lethal and sublethal effects on avian and mammalian wildlife species, toxic algal blooms might disrupt food chains in wetland ecosystems, thereby indirectly affecting animal health by reducing food supplies. Also, secondary botulism die-offs triggered by HAB-induced mortality of invertebrates, fish, or birds may severely affect avian populations, but this avenue of impact has not been well documented.

Fish mortalities are the most frequent animal impact of HAB events. In the winters of 1997 and 1998, millions of fish washed up onto the Texas shore, with more than 21 million reported in 1997 alone. The red tide dinoflagellate *Gymndinium breve* was found to be the cause. The accumulation of dead fish along beaches of the Gulf is not unusual however, as coastal communities and counties on Florida's western coast have had to maintain active beach-cleaning activities to dispose of rotting fish for the last forty years. To facilitate the rapid return of Florida's beaches to recreation and tourism, millions of dead fish have to be removed to landfills or turned under tons of beach sand. Numerous other HABs species kill fish. The flagellates *Heterosigma akashiwo* and *Chattonella antiqua* as well as two diatoms, *Chaetoceros convolutus* and *C. cavicornis*, are frequently found in fish pen mariculture operations, leading to near instantaneous mass mortalities of the densely aggregated populations. The problems caused by these species are so damaging that the mere knowledge that they have been detected locally can foreclose any possibility of fish pen mariculture as a viable industry in that area.

Mass mortalities, greater than 1 billion schooling fish in the last ten years in North Carolina coastal waters alone, have been attributed to exposure to *Pfiesteria piscicida.* This dinoflagellate was also implicated as the responsible agent for kills of approximately 30,000 fish in Maryland's Eastern shore tributaries in 1997. Laboratory experiments indicate that crab shell deformities might also occur following exposure to toxic stages of the organism.

Affected wildlife may serve as suitable models for the study of physiologic and pathologic changes produced by algal toxins and may also provide insights into the toxic effects in humans and wild and domestic mammals. Because of their position in the food web, sickness and death in these higher-level aquatic animals may serve as an early indicator of toxin-producing algal blooms.

HAB impacts on the lower trophic levels of an ecosystem are also common and can alter feeding behaviors, ingestion rates, and therefore plankton community composition. A common coastal ciliate, *Favella*, swims erratically and may burst following exposure to the diarrhetic shellfish poison-producing dinoflagellate *Dinophysis.* Some copepods, small shrimp-like organisms, may completely avoid toxic HAB species, may ingest some species only to reject them, or may ingest HABs resulting in narcosis and/or lower egg production. When HABs, like the brown tides, become very abundant light penetration may be reduced, effectively shading out other plants like submerged aquatic vegetation (SAV). Loss of SAV can have dramatic impacts on coastal ecosystems as these grass beds serve as nurseries for the food and the young of commercially important fish and shellfish populations.

The over-accumulation of plant life, primarily macroalgae and phytoplankton, can lead to high rates of plant decomposition. Bacteria require oxygen for the decay of the plant material, and this can result in bacteria stripping the oxygen from local waters. These HAB events need not produce toxins to cause detrimental impacts; the oxygen required for to breakdown the mass of algal cells is so great that most or all of it is stripped out of the water through decomposition. Some of the HABs that result in visible water discoloration (e.g., mahogany tides of the Chesapeake, red tides of the Gulf of Mexico, red sea slicks off southern California) often produce very low oxygen levels (hypoxia) during the night. This reduction of oxygen can be severe enough that the area may not be suitable for normal fish, shellfish, and other oxygen-requiring animals.

ECONOMIC CONSEQUENCES OF HABS

HABs result in wide-ranging impacts on fisheries, public health, and coastal aesthetics, All of which involve some degree of economic loss. Overall, the economic impacts from HABs are diverse and large. Perhaps more important, they are recurrent, and they show every sign of increasing as the number of toxic and harmful algal species grows and our reliance on the coastal zone for aquaculture, commerce, and recreation expands. Prudent investment in research and monitoring can do much to reverse this trend and to reduce the annual impacts.

Most coastal states have neither conducted economic analyses of HABs nor collected data that can be used to generate reliable quantitative economic impact estimates. In many cases, the complex physical and ecological characteristics of the coastal environment make it difficult to determine whether an algal bloom is the immediate and relevant cause of certain coastal phenomena such as fish kills, oxygen depletion, or seagrass dieoffs. Moreover, local experts often differ substantially in their opinions about the magnitude of economic impacts from HABs. In addition, there may be indirect or hidden costs such as constrained development and lost marine recreational opportunities.

There have been several efforts to estimate losses associated with individual HAB events. To date, however, only one study has attempted to compile a national estimate. Researchers at the Woods Hole Oceanographic Institution recently conducted a study of the estimated average annual “economic impacts” resulting from HABs in the United States .[81] This study represents the first attempt at developing a coherent estimate of the economic impacts of HABs in the United States. The analysis is based mainly on a survey of experts from individual coastal states and from the literature, covering the period from 1987 through 1992, a period during which the most consistent estimates could be made from the most reliable data. The study compiled estimates from independent studies and develops estimates from such elements as the cost of medical treatments and lost revenues due to the closure of commercial fisheries. In most cases, these estimates are of direct costs or lost gross revenues; they are not a measure of lost economic surpluses. Moreover, the study did not employ regional input-output methods to estimate indirect and induced economic effects (e.g., it does not develop estimates of economic impacts using multipliers).

The Woods Hole research team classified the types of economic impacts as follows: (1) public health impacts; (2) commercial fishery impacts; (3) recreation and tourism impacts; and (4) monitoring and management costs. A presentation of the annual economic impacts from HABs for each of these categories is provided in Table 1. The total annual impact is approximately $42 million, ranging from $26 to $73 million over the 6-year interval. (Unless otherwise indicated, all estimates are reported in 1999 US dollars.)

It should be recognized that outbreaks of individual blooms can cause severe economic impacts that equal or exceed the annual averages for the study interval selected by the Woods Hole team. For example, a 1976

New Jersey red tide caused losses in the commercial shellfish harvesting and processing sectors estimated at more than $1 billion in 1999 dollars. Similarly, the 1997 outbreaks of *Pfiesteria pisicida* in the Chesapeake Bay is estimated to have cost the Maryland seafood and recreational fishing industries almost $50 million. Notably, this single event exceeds the annual average of HAB impacts for the entire nation.

The *P. piscicida* outbreaks are a good example of what has become known as the "halo" effect. In general terms, the halo effect refers to a situation in which seafood consumers switch to substitute foods because of concerns about the possible contamination of seafood due to one or more HAB events. Similarly, tourists may choose an alternative vacation destination because of the risk of a HAB event. Because there may be considerable uncertainty about the pathways through which the public health may be affected adversely by a HAB event, a halo effect may occur for seafood that is not even contaminated. As in the Maryland Pfiesteria case, the economic impacts associated with a halo effect can be substantial. Importantly, the halo effect may be ameliorated through the application of appropriate methods of monitoring, management, and risk communication. A halo effect typically affects producers of seafood or, analogously, producers of recreation and tourist services. Because consumers switch to other foods or to other recreational activities, the halo effect may not be as serious for consumers as it is for producers.

Estimates of Economic Impacts by Category of Impact

Public Health Impacts. Human sickness and death from eating tainted seafood results in lost wages and work days. Costs of medical treatment and investigation also are an important part of the economic impact caused by such events. The Woods Hole team estimates that total public health impacts from HABs ranged from $17 to $23 million, averaging $20 million per year over the six year interval.

Cases of sickness and death from shellfish toxins are probably the most clearly documented among the different types of HAB impacts, because these cases are recorded by public health agencies in individual states as well as at the federal level. Average annual public health impacts due to shellfish poisoning from HABs are estimated at $1 million (caused by PSP, NSP, and ASP).

Another problem caused by toxic algae is the ciguatera fish poisoning. Ciguatera affects predominantly the residents of, and visitors to, Florida, Hawaii, Puerto Rico, the US Virgin Islands, Guam, and the Marshall Islands (a former U.S. trust territory). Over the study interval, the economic impact of ciguatera poisoning varied from $16 million to more than $23 million per year, averaging $20 million. These estimates are probably low, because ciguatera poisoning that occurs from exports of tropical fish to other jurisdictions may not even be diagnosed never mind reported. Further, some seafood companies purchase insurance to cover potential ciguatera-caused liabilities, and there may also be undocumented court costs associated with ciguatera-related litigation.

Commercial Fisheries Impacts. Commercial fishery impacts from HABs include wild harvest and aquaculture losses of fish and shellfish resources due to NSP, PSP, ASP, ciguatera, and brown tides. Annual impacts vary from $7 to $20 million with average annual impacts of $13 million. Estimation of commercial fishery impacts is complicated by the transfer of shellfishing effort from closed areas to those that remain open or because fishermen switch to other fishing activities. Finally, the effects of delayed harvesting, as with temporary beach closures due to PSP, could not be estimated with any precision.

Measuring the economic impacts of wild fish kills is problematic because many involve so-called "trash" fish that, by definition, have no market value. Also, the ultimate causes of fish kills often are unclear. For example, fish kills caused by toxic *Pfiesteria piscicida* events undoubtedly occurred in North Carolina during the six-year study interval, but state officials cannot specify with certainty which events were caused by *P. piscicida* and which were due to other causes, such as low dissolved oxygen.

Another issue is that some currently untapped fishery resources may have economic value that could be realized in the absence of HAB events, but estimates were not included. A prominent example is the shellfish resource of coastal Alaska, permanently quarantined due to persistent PSP toxicity and the logistics of sampling distant or remote resources for toxins. The in-place value (i.e., gross revenues) of the sustainable yield of presently untapped shellfish from Alaskan waters has been estimated to be $25-40 million per year, but because of the PSP closures, there is essentially no wild harvest industry in that state. However, in order for such "lost opportunities" to be counted legitimately as economic impacts, these fisheries must be demonstrated to be commercially viable. A plausible alternative reason for non-exploitation is that they are not profitable fisheries because there is insufficient demand or harvesting is uneconomical.

Tourism and Recreation Impacts. In 1991, a study by the US Departments of Commerce and the Interior estimated that expenditures by recreational fishermen for travel, food, lodging and equipment were 67% greater than the value of commercial fish landings. Although many experts argue that the impacts of HABs on recreation and tourism are important and potentially large, there is little available data describing the size of the impacts. Clearly, the economic impacts of HABs on recreational and tourism activities deserve substantially more attention than they have gotten to date. In Florida, for example, recurrent red tides have been estimated to cause over $20 million in tourism-related losses every year. These impacts, as well as similar losses in Texas and other areas, are not well-documented and thus quantitative impact estimates were not included in the Woods Hole study. Estimates of economic impacts on recreation and tourism during the 1987-92 period range from zero to $28 million. The annual average is $6 million. Efforts to measure recreation and tourism impacts must be undertaken at the local level because local environmental and socioeconomic conditions are critical determinants of changes in recreational benefits.

Monitoring and Management Costs. It is often the case that water monitoring tasks, including shellfish testing for PSP, NSP, and ASP are spread across different divisions of state government, making it difficult to compile data on costs. Further, monitoring activities for both HABs and other water quality testing, such as shellfish sanitation, often are conducted by the same personnel. As a result, it is difficult to factor out those costs related specifically to HAB monitoring and management. Annual average monitoring and management costs for HABs are estimated to total $2 million, distributed among twelve states and one territory: Alaska, California, Connecticut, Florida, Maine, Massachusetts, New Hampshire, North Carolina, New Jersey, New York, Oregon, Puerto Rico, and Washington. These costs include the routine operation of shellfish toxin monitoring programs, plankton monitoring, and other management activities. It is important to note that expenditures made to improve monitoring and management are likely to result in decreases in impacts in the other categories.

The Economic Impact of Pfiesteria piscicida on Seafood Industry Sales & Recreational Fishing 81
During the summer of 1997, several fishkills resulting from blooms of the harmful algae *Pfiesteria piscicida* occurred in a few river systems in Maryland. Estimates are that 30,000 fish died. An unspecified number of fish showed lesions that some think were related to *P. piscicida*.. These blooms were confined to small areas, only a few commercially and recreational important fish species were affected, and only a few commercial fishermen complained of health effects. Despite this and the fact that there is no evidence that *P. piscicida* toxin is a concern for consumers of seafood from affected areas, the economic impact of Pfiesteria was extraordinary.

The Maryland Sea Grant Extension Program, in conjunction with the Maryland Department of Agriculture's Office of Seafood Marketing, attempted to quantify declines in Maryland seafood sales resulting from the public's concern about the safety of Chesapeake Bay seafood during the 1997 outbreaks of *P. piscicida.* A survey was mailed to retail and wholesale seafood businesses in the state. These businesses were asked to provide monthly sales figures for both the previous year and the current year. The compilation of this data allowed the establishment of a baseline (sales prior to any concerns regarding *P. piscicida*) with which to compare sales during the height of public concern regarding *P. piscicida.* Seafood sales in 1997, prior to the *P. piscicida* outbreak, were running ahead of the 1996 baseline by about 7.4% and would have totaled $253 million. Actual 1997 seafood sales were $210 million, a loss in revenues of $43 million. Firms that specialized in Chesapeake Bay products had a greater reduction in sales (12.8%) than those that sold products from other areas (9.4%), but both types of firms were greatly affected.

The recreational fishing industry also felt the far-reaching impacts of *P. piscicida.* The annual NMFS Marine Recreational Fishing Statistics Survey data indicate that in 1997, recreational fishing on private or rented boats was 10% higher than the baseline (1990-1996 average) and shore-based fishing was up 28%. In contrast, party and charter boat fishing was 24% below the baseline and there were 35% fewer trips taken in 1997 compared with 1996. The loss of roughly 28,000 party/charter boat trips, presumably due to concerns regarding *P. piscicida*, translates into lost revenues to party/charter boat captains of approximately $2.2 million. Total expenditures of party/charter boat fishermen were reduced a total of $4.3 million. The lost benefit to the fishermen on the party/charter boats due to the loss of a fishing opportunity was approximately $1.9 million.

Overall, the aggregate impact of the *P. piscicida* outbreak in just a four month period in 1997 approached $50 million in Maryland.

CAUSES OF HARMFUL ALGAL BLOOMS

Although few would argue that the number of toxic blooms, the economic losses from them, the types of resources affected, and the number of toxins and toxic species have increased in over the last twenty years in the United States and around the world, opinions differ with respect to the reasons for this expansion.[82, 83] Humans may have contributed to the global HAB expansion by transporting toxic species in ship ballast water or by dramatically increasing aquaculture activities.[84] Other “new” bloom events may reflect indigenous populations that were discovered because of better detection methods and more observers.[85] Some scientists hypothesize that increased nutrient loads to coastal waters stimulate low-level ambient populations of microscopic and macroscopic algae to initiate a bloom. Others scientists postulate that the nutrients that humans supply to coastal waters are delivered in proportions that differ from naturally occurring ratios, such that we may be altering algal species composition by favoring certain groups.

Because HABs are so varied, many with complex life histories, it is likely that no single environmental condition stimulates HAB blooms, but rather nutrient enrichment, seasonal temperature and salinity changes, storm events, or a combination of factors initiate bloom formation.

Life Cycles of HABs

The characteristic life cycles ofsome harmful algal species help to explain HAB formation. Many produce resting stages, that occur when ambient conditions become stressful to the organisms. These sink to the bottom and lie dormant until favorable growth conditions return. Examples of this behavior can be seen in the PSP-producing dinoflagellate *Alexandrium* in the Gulf of Maine, Pacific Northwest, and Alaska. The cysts of this dinoflagellate transform into new swimming populations each spring when overlying waters warm and light levels increase. The transformation from resting stage to swimming plant cell coincides with increasing levels of nutrients delivered to coastal areas in winter melt waters, creating conditions favorable for massive population increase. This sequence of events has made it possible to predict the occurrence of PSP for a given year at sites that have a history of *Alexandrium.* Cyanobacterial akinetes, have similar responses to changing conditions, resulting in rapid population growth as temperatures, light, and nutrient levels increase. The "ambush predator" dinoflagellate *Pfiesteria piscicida* produces cysts that may be stimulated to transform from cysts to icthyotoxic zoospores by some as yet unknown substances that indicate suitable prey is nearby.

Roles of Circulation and Other Physical Factors

The clearest examples of circulation-driven blooms in US waters are *G. breve*, the organism responsible for NSP in the Gulf of Mexico, and *A. tamarense,* the organism responsible for PSP in the Gulf of Maine. Red tides caused by *G. breve* have been recorded in the Gulf of Mexico since the late 16th century, suggesting that anthropogenic nutrient loadings are not responsible for blooms of this species. Instead, regional circulation in the eastern Gulf of Mexico is thought to deliver sparse, offshore populations of *G. breve* to the shelf break on Florida's western coast, allowing for growth, accumulation, and "red tide" formation. In 1987-1988, blooms of *G. breve* were transported to NC's outer banks via the Gulf stream, and onshore through a Gulf Stream eddy. This mass transport (advection) of the red tide has been documented through examination of remote sensing images collected during the period.[86]

Alexandrium, common along the Canadian coast, was likely delivered to the northern and eastern Gulf of Maine from the Bay of Fundy. Because of the organism's unique life cycle, which includes a resting stage called a cyst, resident populations of *Alexandrium* are now entrenched in Maine's river mouths. These excyst or "hatch" each spring to give rise to new toxic populations which are transported to the south and west.

HAB events are commonly associated with stratified water columns, subject to long periods of low flow and little mixing. These conditions are often found in water bodies that have a long residence time in a restricted area with little exchange with outside water sources like the open ocean or rivers. Extreme examples of this situation are the lagoonal systems, such as the Texas coastal bay of Laguna Madre near Galveston, TX as well as the Peconic estuaries in Eastern Long Island, NY which have experienced BTBs with concentrations of cells exceeding millions per liter. The development, persistence, and impact of these BTBs can be largely attributed to the physical conditions that result in low freshwater input and poor exchange with coastal waters. Both of these shallow bay systems are in ocean-flooded, low-lying areas with only minimal amounts of freshwater input, primarily from groundwater.

Cyanobacterial blooms, common occurrences in many US tidal rivers, are associated with poorly flushed, stable systems. Tidal rivers that experience these blooms are often nutrient-enriched, slow-moving systems where freshwater inputs mix very gradually with salty coastal ocean waters. During the high light, calm water conditions of summer, cyanobacteria float to the top of the water column, creating "floating scums." In more saline areas, the cyanobacteria may be replaced by another group of phytoplankton. In the Chesapeake Bay and it tributaries, these occur as "mahogany" or "red" tides comprised of millions of swimming dinoflagellates.

Regional circulation patterns that carry nutrient-rich deeper waters into shallow coastal zones can also result in HABs. Classic examples are the massive dinoflagellate and ciliate blooms that occur near upwelling zones off coastal Peru, but similar coastal circulation patterns have been suggested as the cause of toxic blooms of domoic acid-producing Pseudo-nitzschia off southern California. The coincidence of high levels of domoic acid in shellfish in the Northwest and seasonal upwelling also suggests that the delivery of deep nutrients to near surface waters in these regions may be potentially responsible for the annual occurrences of ASP.

Motile species, including many of the harmful algae, can also become concentrated at the point where different water masses converge or form a front. Some motile dinoflagellates maintain themselves in near-surface waters at the edge of fronts, accumulating above the downwelling waters. The aggregations of *Noctiluca scintillans* off southern California and *Prorocentrum minimum* in Chesapeake Bay are examples of this phenomenon. Water masses separated by different densities, velocities, or shear forces may concentrate harmful species. For example, three distinct layers of HABs, *Dinophysis*, *Alexandrium*, and *Pseudo-nitzschia* have been observed in distinct narrow layers in the water column off East Sound, WA.[87]

Nutrient Enrichment and HABs

Nutrient enrichment has been suggested as the cause for increasing frequency of HAB events along our coasts. It is very difficult to determine if nutrients have played this role, however, because of the lack of historical data, both with regards to nutrients and abundance of HAB organisms. Many HAB events are initiated offshore, where nutrients are low. There are strong indications, however, that nutrients can enhance the growth of some HAB species found in US waters. The addition of nutrients to coastal waters can also stimulate the overgrowth algae and may result in conditions of low or no oxygen (hypoxia or anoxia, respectively).

Manipulation of coastal watersheds for agriculture, industry, housing, and recreation has drastically increased nutrient loadings to US coastal waters. Just as the application of fertilizer to lawns leads to enhanced plant growth, marine plants (algae) respond to the nutrient enrichment of our nation's coastal waters. While enhanced growth of plants may increase the productivity of local fish and shellfish stocks up to a point, excess production can lead to an overabundance of algae that can exceed the capacity of grazers (e.g. fish or snails) to keep pace.

Pfiesteria piscicida, the organism associated with fish kills and fish lesion events in Maryland in 1997 and North Carolina for much of the present decade, has been found in tributaries with high ambient levels of nutrient and dissolved organic matter (sugars and amino acids) relative to similar waterways. Elevated populations of this HAB species have been found immediately downstream of sewage outfalls and discharges from hog farms. These observations, coupled with laboratory results showing enhanced growth of *P. piscicida* after exposure to both inorganic and organic nutrients, suggest a linkage between high nutrient load and abundance of this potentially toxic dinoflagellate.

Blooms of *Pseudo-nitzschia* appear to be stimulated by nutrients. Nutrient inputs to the Gulf of Mexico from the Mississippi have increased significantly since the 1950's and historical data show large increases in the abundance of this organism in the same time period.[88] *Pseudo-nitzschia* species are among the dominant species of phytoplankton in the nutrient-rich plume of the Mississippi River and reach peak abundances in the spring when river flow and nutrient levels are highest.[89] Along California's coast, nutrients delivered to surface waters from natural coastal upwelling have been responsible for many *Pseudo-nitzschia* blooms. In 1998, the *Pseudo-nitzschia* blooms that caused numerous sea lion mortalities may have been partially a result of record levels of river discharge that carried high nutrient loads into Monterey Bay.

Nutrient enrichment also plays a role the proliferation of coral reef macroalgae. Macroalgal blooms occur in nutrient enriched estuaries and nearshore areas. Storm events periodically dislodge massive amounts of the macroalgae, depositing it onshore, with concomitant hypoxic and anoxic conditions inshore and mounds of decaying plant on beaches.

APPROACHES TO REDUCE, MITIGATE, AND CONTROL HABS

Management options for dealing with the impact of HABs include reducing their incidence and extent (prevention), stopping or containing blooms (control), and minimizing human health risks and reducing the losses of resources or economic values (mitigation).[90] In 1996, the National Oceanic and Atmospheric Administration (NOAA) and the Department of the Interior (DOI) requested an assessment on the status of HABs in the US and options for their prevention, control, and mitigation. The assessment was undertaken to inform policy at Federal, state and local levels might take in dealing with the increasingly serious problem of harmful algal blooms. Representatives from NOAA, DOI, the National Fish and Wildlife Foundation, and academic scientists worked in partnership to produce the document, *Harmful Algal Blooms in Coastal Waters:*

Options for Prevention, Control and Mitigation.[91] Regional meetings were convened in Texas, Washington, and Florida to bring together scientific experts, managers, and user constituencies to provide input to the assessment report.

The assessement report offered numerous specific recommendations and generally concluded that the following were needed: improved precautions for the protection of human health, more concerted efforts to manage activities which may cause HABs, and renewed consideration of strategies to control blooms once they occur. The assessment also focused attention on the control of HABs and the evaluation of control techniques in the context of risk assessments (i.e. similar to those applied in the agricultural industry).

The report also noted that research being initiated by federal agencies on the Ecology and Oceanography of Harmful Algal Blooms program(ECOHAB) will contribute basic information on the causes and behavior of HABs which will ultimately lead to prevention, control, and mitigation strategies. To complement this program, federal and state agencies with responsibilities for resource management, environmental protection, and public health should support research directly addressing prevention, control, and mitigation.

Prevention

Prevention refers to environmental management options for reducing the incidence and extent of harmful algal blooms before they begin, not controlling or mitigating them after they occur. One approach to prevention is controlling pollution inputs to coastal waters, since one explanation given for the increased incidence of HAB outbreaks is that these events are a reflection of increased pollution and nutrient loading. It is true, in some areas where pollution has increased dramatically, that coastal waters receiving industrial, agricultural, and domestic effluents high in plant nutrients have experienced a general increase in algal growth. For these waterbodies, the report recommends reducing nutrient inputs.

With respect to research needs, the potential stimulatory influence of anthropogenic nutrient inputs on HAB incidence is certainly one of the more pressing unknowns we face, and it will require a focused commitment of resources and effort greatly in excess of what has been devoted to the topic until now. Time-series analysis of existing databases for phytoplankton communities and variables such as pollutants is required, and where such data are lacking, long-term monitoring programs of at least 10-years duration must be initiated in key regions where anthropogenic changes are anticipated. Laboratory studies of the stimulatory effects of chemicals contained in effluents or terrestrial runoff are also needed, as are kinetic studies and other experiments that can quantify the nutritional requirements and uptake capabilities of HAB species.

Other strategies which can lead to bloom prevention include regulation of freshwater flows (since some blooms are linked to either high or low salinity waters), modification of water circulation (for those HABs where restricted water exchange is a factor in bloom development), and restrictions in species introductions (such as through regulations on ballast water discharges or shellfish and finfish transfers for aquaculture).

Control

Although the significance and recurrence of HAB phenomena would seem to justify bloom control as a high-priority research topic, virtually no focused research has been undertaken on this topic in the United States for nearly 40 years.[90, 91] The objective of past and ongoing research on HABs in the United States has generally been to seek an understanding of the fundamental biological, chemical, and physical processes underlying blooms and their impacts. The rationale for this approach is that such understanding is essential if we are ever to manage or mitigate blooms (i.e. we can't control what we don't understand). In contrast, human efforts to control insects, diseases, and weed species are common on land. The reasons for the lack of similar efforts to control marine pests are many, but in general, reflect concerns about costs, effectiveness, and environmental impacts.[91] There are numerous success stories in agriculture where biological control or integrated pest management have eliminated problem weeds or insect pests, often over millions of acres and without significant adverse impacts on the environment.[92] Another factor is that no federal agency has been given the mandate for marine pest management in the way the US Department of Agriculture has been assigned this responsibility for the terrestrial pests that threaten agriculture. Approaches to direct bloom control include chemicals, flocculants, and biological control agents.

Attempts to use chemicals to directly control red tide cells in blooms encounter many logistical problems and environmental objections. The dispersion of copper sulfate over 16 square miles using crop dusting planes in a 1957 Florida red tide control effort highlights several of these problems, the most significant being that the chemicals are likely to be non-specific and thus will kill co-occurring algae and other organisms indiscriminately.[93] Efforts to find a magic chemical bullet that will somehow kill only a specific, targeted HAB species may be futile, as it is difficult to imagine a unique physiological target for a chemical that would only be lethal to a single phytoplankton species. Even if such a chemical were found, objections on environmental grounds are likely to be significant. Each candidate chemical will require extensive testing for lethality, specificity, and general safety, and each must surmount regulatory hurdles such as those imposed on industrial discharges to coastal waters. Although direct chemical control of red tides may not be a strategy of choice given other more benign alternatives, the success of this approach in terrestrial systems (e.g. application of herbicides and pesticides) suggests that it should not be completely ruled out.

A flocculant is a material that, when added to water, scavenges co-occurring particles as it falls to the sediments below. Inorganic flocculants (e.g., aluminum sulfate or various ferric salts) are commonly used to purify fresh water in reservoirs. One mineral flocculant that shows considerable potential in coastal waters is clay. When added to seawater, clay particles absorb inorganic and organic materials, algae, and other particles to form a floc which falls to the sediments. In field trials, Asian scientists have used clay to treat natural red tide blooms on several occasions, including major blooms in Korea covering 100 square miles. For this strategy to be fully evaluated, studies are needed which examine the effectiveness of this strategy on US HAB species and the environmental effects of the treatment, especially the potential release of toxin during flocculation and the impact of sedimented cells and clay on bottom-dwelling organisms. Some of these studies are presently underway, but it will be several years before the scientific results are sufficient to justify pilot studies and field tests.

Biological control is another option worthy of investigation. There are a variety of organisms that could conceivably be used to control HABs, but in reality, this approach has many logistical problems and is far from the application stage. Introductions of non-indigenous species or strains pose unknown risks and may be irreversible. Biological control is used extensively in agriculture, but there is still considerable opposition to the concept of releasing one organism to control another. This concern is likely to be greatly magnified if the marine environment is to be the site of the release, as there is little precedence for such activities. Despite examples where such an approach has had negative long-term consequences on land, there are cases where the approach has been both effective and environmentally benign (e.g., sterile male releases for control of the Mediterranean fruit fly). The concept deserves some consideration in marine systems, focusing on control agents such as zooplankton, bacteria, parasites, and viruses. Viruses, for example, have the potential to be highly specific and effective control agents. They are abundant in coastal seawater and are recognized as being significant in the dynamics of phytoplankton blooms. They replicate rapidly, releasing hundreds of viral particles when a host cell is disrupted. Another important feature is that viruses tend to be host-specific. This means that a single algal species could be targeted, leaving closely related, co occurring organisms unaffected. In reality, however, viruses are sometimes so host-specific that they are unable to infect different genetic strains of the same host species.

With respect to future research, studies are needed to determine if viruses, bacteria, or parasites exist that can be effective pathogens to targeted HAB species. Once pathogenic isolates are established, they must be tested for specificity and efforts made to understand the dynamics of infection and replication. The environmental implications of the release of non-indigenous organisms will need to be fully understood before this strategy could be tested in the field.

Mitigation

Mitigation involves steps taken to minimize human health risks, ecosystem damage, or fisheries losses from HABs that are otherwise not prevented or controlled. Highly effective tools in this regard are monitoring programs that detect toxins in different fisheries species to provide either advance warning of outbreaks or to delineate areas that require harvest restrictions. This is predominantly a state activity, coordinated with the Food and Drug Administration (FDA) through the Interstate Shellfish Sanitation Conference (ISSC). States differ in their monitoring strategies. Some, such as Maine, Massachusetts, Florida, Oregon, and Washington, monitor their shellfish seasonally at key stations along their coasts, and then close specific areas to harvesting when toxins approach dangerous levels.[94] Other states (e.g., Alaska) maintain permanent shellfish closures due to persistent toxicity or the logistical difficulties of monitoring remote stretches of coastline. Recent concerns about Pfiesteria-like organisms have led a number of East Coast states to implement monitoring programs for plankton and fish in coastal estuaries and bays, again as an early warning strategy.

All of these monitoring programs are expensive, but they do provide an important measure of safety to consumers and to the fisheries industries. However, one important result of the HAB expansion over the last several decades is that the monitoring programs of many states are under severe financial pressures, due to flat or declining budgets and the need to monitor for more toxins in more organisms over larger areas. Programs that formerly monitored only a single toxin in one or two shellfish species now must assay for several toxins in multiple shellfish species, as well as crabs, snails, and other resources.

Development efforts are therefore needed to make monitoring programs more efficient while providing better coverage in time and space. This will require research on new technologies such as: 1) remote sensing (to detect and track blooms); 2) molecular probes (to identify and quantify cells and toxins in a rapid or even automated fashion); 3) improved toxin assay methods (to provide fast, accurate, and inexpensive methods for use by agencies, industry, and consumers); and moored or automated sampling arrays that can detect cells or toxins and telemeter the information to shore. These are but a few examples of areas where funding will provide practical benefits to consumers and to the fisheries industry.

Another important mitigation activity is risk communication. Many countries or regions have programs in which the public, the media, and the medical community are kept fully informed about the risks (and misconceptions) of HABs and their toxins. Doctors and hospitals should be better informed and prepared to recognize and treat individuals suffering HAB toxicity. Responsible public education and communication should receive increased attention so that those visiting or living on the shore or consuming seafood are better informed about the risks and can be cautious, but not unduly alarmed.

Other examples of mitigation strategies include improved modeling and forecasting to allow more time to protect resources and avoid risks, and the restoration of affected resources (such as reseeding of hatchery-reared scallops in the Peconic Bay system in New York after mortalities resulting from brown tide).

Research

Concurrent with the perceived increase in bloom incidence has been an increase in research on HABs, but much of it has been on a fundamental level involving efforts to understand the physiology, genetics, toxicology and oceanography of these phenomena. Practical initiatives such as those directed to prevention, control, and mitigation, have not been as prominent. This is in part because the largest US funding program for HAB research is ECOHAB which addresses the ecology and oceanography of HABs. There is no question that this emphasis is justified, since it is not possible to consider mitigation or control strategies without a thorough understanding of the physical, chemical, and biological factors that regulate bloom formation. However, research on some of the HAB species has progressed to the stage where it is prudent to begin a parallel line of investigation on practical mitigation strategies.

One aspect of the increased public and agency attention on HABs in recent years has been the expectation by affected groups that bloom control should be a high priority. One example of the heightened expectations of the public and their frustration with the pace and direction of science is the formation of START (Solutions to Avoid Red Tide), a non-profit citizen organization dedicated to funding and promoting efforts to control red tide in Florida. START's goal is to increase government, science, business, and the public's awareness of the disastrous effects of red tide on human health, the environment and the economy; and to find funding for research and testing of possible solutions to control and mitigate red tide without negatively impacting the environment. START has become a powerful political force that has been directly involved in obtaining federal and state funding for programs that focus on the prevention, control and mitigation of HABs and their impacts.

UNCERTAINTIES, DATA GAPS AND RESEARCH NEEDS

Over the past decade there has been an ongoing effort by Federal Agencies working with the science community, and to a more limited extent state public health and fisheries concerns, to identify uncertainties and data gaps and the research needed to address the problem of HABs in US coastal waters. There is general consensus that a long-term commitment and significant support for more work in areas of marine biotoxicology, ecology and oceanography, prevention control and mitigation, economic assessments, and public health is required.

Reports such as *Marine Biotoxins and Harmful Algae: A National Plan*;[95] *The Ecology and Oceanography of Harmful Algal Blooms A National Research Agenda*;[96] *Harmful Algal Blooms in Coastal Waters: Options for Prevention, Control and Mitigation*,[90] and *National Harmful Algal Bloom Research and Monitoring Strategy: An Initial Focus on Pfiesteria, Fish Lesions, Fish Kills and Public Health*,[97] have covered the uncertainties, gaps, and research needs in detail. Findings from these studies are briefly summarized below along with more recently recognized issues. Whereas there has been some progress in addressing the recommendations in these reports as a result of the Interagency ECOHAB Program, this effort is in its early stages and the scope of the program has been very modest relative to the extent of US HAB problems.

Marine Biotoxicology

Marine biotoxins and harmful algae represent a significant and expanding threat to human health and fisheries. A working group identified the following areas where uncertainties, lack of information, or technology developments impede progress on solving HAB problems:[95]

Deficiencies related to the biotoxins. Toxin standards are largely unavailable; standard sample preservation and handling protocols do not exist; existing assay methods are inadequate for monitoring and research; molecular pharmacology and pharmacokinetics of marine biotoxins are poorly understood; diminution or loss of toxin production can occur in laboratory algal cultures; mass culturing of most toxic species is difficult, and the availability of isolates of toxic or harmful algae is limited.

Lack of information on impacted fisheries resources and protected marine resources. Toxin uptake, metabolism, and depuration in shellfish, fish, and other marine animals is poorly known; toxin sensitivities of different life history stages, and long-term effects of algal metabolites on growth, reproductive success and recruitment are unknown; movement of toxins through the food web is poorly understood; databases are inadequate and not readily accessible to potential users; methods for rapid field assays of fish or shellfish are lacking; toxin standards are often unavailable; analytical methods for toxin detection in animal tissue need improvement.

- Inadequate mechanisms and knowledge to protect public health fully. Early warnings of known and unknown toxins are required to protect consumers and industry; assay methods need improvement; toxin standards are not always available; sampling programs are inadequate for bloom detection or characterization; the extent of seafood poisonings is poorly documented; the fate and metabolism of toxins in humans is unknown.

Ecology and Oceanography of Harmful Algal Blooms

HAB events are characterized by the proliferation and occasional dominance of particular species of toxic or harmful algae. As with most phytoplankton blooms, this proliferation results from a combination of physical, chemical, and biological mechanisms and interactions that are, for the most part, poorly understood. Some HABs are unique, however, due to their production of toxins and the manner in which they affect co-occurring organisms and alter food-web function.

The National Plan recognized that there were significant impediments to solving HAB problems because of information lacking about toxins, their public health risks, and their impacts on fisheries. In addition, the National Plan report also recognized that a basic understanding of the ecology and oceanography of harmful algal species was largely lacking. As a response to this information gap, a workshop was co-sponsored by NOAA and NSF to develop a national research agenda to guide activities in the specific area of HAB ecology and oceanography. The findings of this working group were published in the 1994 ECOHAB report, which detailed data gaps and research needs in this area. Overall, the scientific community identified need for further studies of HABs on the cellular, population, and entire ecosystem levels. These major research gaps present significant challenges to the management and mitigation of HABs However, information derived from research focused on these areas could serve as the basis for control, mitigation, and management decisions in the future.

The Organisms*.* Studies at the cellular level are necessary to further understand HAB population dynamics and their toxic or harmful effects. In order to conduct such studies, scientists must be able to isolate a single species from mixed algal assemblages, and grow the algae in pure culture. Such cultures are essential to examine the physiological, biochemical, genetic, and behavioral features of the algal species. This information will allow researchers to better identify HABs in the field, and address such data gaps as life history stages, physiological responses to environmental changes, and the biosynthetic pathways of toxin production. Other recommendations are:

- Develop methods to rapidly and accurately identify, enumerate and physically separate HAB species from mixed phytoplankton assemblages.
- Identify the life history stages of major HAB species, determine what factors control transi tions between those stages, and establish the role of the stages in bloom dynamics.
- Characterize the physiological responses and tolerances of HAB species to differing environ mental conditions.
- Develop methods to permit in situ measure ments of species-specific rates of growth, photosynthesis, and nutrient uptake, and to assess the physiological condition of cells at different times and locations.
- Characterize the nutritional requirements, uptake and nutrient assimilatory characteristics of HAB species.
- Determine the functional role of toxins and/or exudates produced by HAB species.
- Define the genetic basis of toxin production, elucidate toxin biosynthetic pathways, and

determine how toxin accumulation in cells is regulated.

- Investigate the mechanisms and importance of motility and other behaviors of HAB species.

Environmental Impacts on Population Dynamics. The influence of environmental factors on the population dynamics of harmful algal species is a research area with significant gaps. Researchers need to determine the factors that govern the initiation, growth, persistence, dissipation and impacts of harmful algal blooms. Mathematical models are appropriate tools for describing bloom dynamics and their relation to the physical environment, such as turbulence and water column mixing. The coupling between physical variables and biological 'behaviors,' such as vertical migration or swimming, has been identified as the key to understanding HAB phenomena. Such studies will require both large-scale field studies and smaller-scale experimentation in the laboratory. Shipboard observations, field programs, satellite remote sensing and moored instrument arrays are strategies for identifying the mechanisms underlying HAB outbreaks. Research efforts focusing on environmental factors influencing bloom dynamics are entirely complementary to studies on the organismal level, and both are necessary to foster a greater understanding of HAB dynamics and impacts.

- Determine the extent to which HAB events reflect increases in growth rate versus physical transport, immigration, and accumulation.
- Determine whether there is a specific suite of physical factors with which known HABs are associated.
- Investigate physical and ecological processes that control the partitioning of nutrients within a system and the relationship between nutrient inputs and population dynamics of HAB species.
- Investigate whether there are specific physical, chemical, and biological regimes or processes that are associated with HAB events
- Determine whether some ecosystems are more susceptible to HABs than others. If so deter mine what makes them unique and whether they share characteristics that can be used to anticipate HAB events in other systems.
- Characterize HAB population dynamics, including the rate processes required in predic tive models of bloom incidence.

Food Webs and Community Interactions. The negative impacts caused by harmful algal blooms result from a complex network of interactions that begin at the phytoplankton community level and extend up through the food chain to the higher trophic tiers (fish and marine mammals). It is important to recognize that harmful algal bloom impacts extend far beyond shellfish and finfish mortality and include subtle, sublethal effects that can change or decimate whole ecosystems. Major research needs include both an examination of the impacts of trophic interactions on selection for, and dynamics of HABs, as well as how blooms influence the ecosystem's trophic structure, processes, and interactions. Scientists seek to understand how competitive interactions between harmful algal species and other phytoplankton contribute to the formation of blooms. Characterizing the role of grazing in controlling, or failing to control outbreaks, is another important research objective. Tracing the pathways of biotoxins through the food web and determining how the timing and frequency of HAB outbreaks affect the community and trophic structure also must be identified. The following are also of importance to understanding HABs, but have received only rudimentary study thus far:

- Determine the extent to which bloom formation results from a breakdown of grazing or from harmful species outcompeting other phy toplankton for limiting resources,
- Determine whether biological controls (e.g., grazers, allelopathy, pathogens) are the cause of bloom termination,
- Investigate how HAB effects on the food web are controlled by toxin dynamics, food web routing of toxins, and the differential suscepti bility of species at higher trophic levels,
- Determine whether chronic, sublethal impacts of HABs are more significant than acute

(lethal) impacts,

- Determine if HAB impacts are controlled by the degree of temporal and spatial overlap between blooms and critical life cycle stages of target species, and
- Determine whether high biomass (non-toxic) HABs adversely impact the food web.

Impacts on Wildlife. The US Fish and Wildlife Service has established the following priorities as their focus for HABs research:

- Understand the ecology of HABs and their impacts on wildlife species. Interagency cooperation among scientists and organizations with different areas of expertise will be crucial to achieving this goal,
- Improve surveillance to increase the likely detection of bloom and wildlife mortality events and increased research efforts to develop improved diagnostic techniques,
- Develop a centralized system for HAB-related mortality reporting and database development, and
- Identify toxic exposure levels, to evaluate physiologic and pathologic effects, and to determine the significance of toxin levels found in the tissues of sick and dead animals during mass mortality events.

Public Health

Research sponsored by the the Centers for Disease Control and Prevention (CDC) has focused on disease surveillance, health care provider education, epidemiologic studies and emerging problems. There is a definite need for improved disease reporting and surveillance. The current passive systems (e.g., reportable disease status, calls to poison information centers) are inadequate to allow more than an estimation of the magnitude of the problem. Active surveillance in appropriate counties or states would allow the public health community to determine appropriate public health response activities. Except in geographic areas where poisonings or other adverse health effects are endemic, health care professionals are not likely to recognize these illnesses in their patients. Health care providers should be made aware of the symptoms of these illnesses so they can be included in diagnostic procedures.

The epidemiology of the human health impact of exposure to algal toxins is in its infancy. There is a need for basic epidemiologic studies, including disease reporting and surveillance as well as for analytic studies (cohort or case control studies). There is little information about either the chronic effects of acute exposure to these toxins or about the long-term effects of more chronic exposures. Also, there is very little information on the environmental health effects (e.g. asthma exacerbations) from exposure to these toxins. From a clinical perspective, there is a need for improved diagnostic tools as well as improved methods of treating these poisonings.

Newly identified diatoms and dinoflagellates from US estuaries are currently being characterized. These microalgae (e.g. Pfiesteria piscicida) may pose unexpected health risks, and epidemiologic studies will be needed to determine whether there are associations between exposure to these organisms or their toxins and subsequent adverse human health effects.

Analysis of Economic Impacts

The difficulties encountered in generating a national estimate of HAB economic impacts underscores the need to formalize the reporting practice and format for HAB events. At present, information about HAB events is fragmentary and inconsistent. The duration, affected acreage, or shoreline length, average toxicity levels, and values of affected coastal resources should be documented for each bloom in order to describe the overall economic significance of the incident. In addition, local and state governments should place much higher emphasis on the quantification of economic impacts. Until local governments become capable of supplying site-specific impact information for each bloom incident, truly comprehensive and detailed national level aggregation of such impacts cannot be realized. Finally, the causes of economic impacts and the degree of their uncertainty should be included in any discussion of economic impacts. The following specific actions are recommended:

- A national workshop should be held to agree on procedures and methods for the economic analysis of HAB impacts,

- The causes of economic impacts and the degree of their uncertainty should be included in discussions of economic impacts. Economic factors affecting the impact estimates should be reported,

- Another national compilation of the economic impacts of HABs should be undertaken for the years following 1992.

Prevention, Control, and Mitigation

In general, the political drive to control HAB phenomena must be strong and rooted in a conviction that the problems are severe, long lasting, and worth the cost and negative environmental impacts of the control strategy. Certain types of HABs seem the most amenable to control (e.g., those in isolated embayments or those which totally dominate planktonic ecosystems so that few co-occurring species will be impacted by the treatment). Likewise, blooms for which discrete initiation zones can be identified, or emergency situations in which impacts are localized and severe seem appropriate for consideration in this regard. It is premature to seek community consensus on whether control strategies are either advisable or ill-advised for HABs, since current research is not yet sufficient to provide the information that resource user groups need to weigh benefits against costs. Research programs on promising control methodologies should be pursued, but these should be concurrent with field and laboratory studies to better understand the ecological mechanisms underlying HABs.

Targeted funding is needed specifically for a program focused on prevention, control, and mitigation. Funding for such a program should be separate from funding for ECOHAB or other ecology programs. The ECOHAB program is designed to support research on harmful algal bloom oceanography and ecology. There are currently no national research initiatives to promote efforts in prevention control and mitigation of HABs and their impacts.

The rationale for this approach is that one reason control strategies have not been pursued is that proposals on that topic are risky and easily rejected in the peer review system. Quite simply, a scientist can maximize his chances of obtaining funding by proposing more studies to understand bloom phenomena rather than to find solutions for those blooms. This is because fears that a control strategy can cause more harm than it is preventing are rampant: fears that an introduced predator or pathogen will become a problem in itself, that the control treatment will indiscriminately kill many co-occurring organisms, or even that the red or brown tides should be left alone because they serve important ecological functions (akin to forest fires) by cleaning out the weak and unfit in an ecosystem. As a result, no focused research on bloom control strategies has been undertaken in the United States for nearly 40 years.

The following steps should be taken to ensure progress on HAB prevention, control, and mitigation:

- Convene a workshop to define the specific science agenda for the prevention, control, and mitigation of HABs. This is needed to take the general recommendations of the 1997 assess ment and refine the ideas into specific areas or themes that are scientifically feasible and worthy of immediate attention. A detailed science agenda is needed by funding agencies as they establish programs in this area.

- Develop partnerships with the private sector, perhaps through cooperative research with industry, since it is private industry that will be focused on practical aspects of HAB research and development. Sea Grant has had several programs of this type that could be used as models of how to involve industry in academic investigations.

- Involve others outside the HAB community in the effort e.g., Agricultural Research Service (ARS) or engineering companies. The ARS in particular may have much to offer given its long involvement in pest control.

- Provide sustained funding for PCM programs, not intermittent support. It must be made clear to the appropriators and the agencies that NOAA is being asked to take this on as a mandate from Congress, and that new funds are needed for this new program. Funds for PCM should not come at the expense of fundamental studies on the biology, ecology and toxicology of HAB species, but should be supplemental.

- Take steps to ensure the program includes efforts to transition these research and applica tion activities from federal sponsored research/ development to the implementation phase where States and industries take on the burden and responsibilities.

- Forge inter-agency partnerships to share the costs and responsibilities of PCM research. These other agencies will need their own appropriations.

- An important issue is not to promise too much in this program—to focus initially on labora tory studies and small, restricted efforts (pilot studies, mesocosms)—a gradual and careful approach. Politicians and agency officials should be made aware of the dangers of expecting too much progress or success, especially in the short term.

It is also important not to rush initial efforts at bloom control. A few disasters in attempted, but premature, bloom control would be a major setback that might cripple this line of research

Addressing Harmful Algae Problems Is a Long-Term Process

The following is excerpted from a General Accounting Office report. [99]

Research on harmful algae is generally long-term. Most ECOHAB-sponsored research projects are just getting under way, including two 5-year multidisciplinary programs to study toxic algal blooms in the Gulfs of Maine and of Mexico. Some delays have been encountered. According to NOAA officials and several key researchers, there has been a significant delay in identifying the chemical composition of the *Pfiesteria* toxins. They stated that researchers cannot get enough *Pfiesteria* toxins to characterize their chemical and molecular structure. Massive amounts of tiny algal cells must be isolated in pure laboratory cultures to produce enough toxins for the analyses. Thus far, the Aquatic Botany Laboratory at North Carolina State University has been the only facility able to provide significant quantities of toxic *Pfiesteria* cultures to the scientific community. According to the laboratory director, funding limitations have precluded the facility from producing sufficient quantities of the toxins for identification and characterization. Until toxin supplies for *Pfiesteria* and other harmful algae are increased and the chemical analyses are completed, other important research objectives, such as developing management and mitigation strategies to minimize the impact on human health and the environment, are unlikely to be achieved. Recognizing that many of ECOHAB's research projects represent long term efforts and are primarily directed to resolving scientific uncertainties, a 1997 scientific panel recommended the creation of a federal program that would complement the ECOHAB program by focusing on the prevention, mitigation, and control of harmful algae. While NOAA, EPA, and other federal agencies have conducted or supported efforts in this area, the efforts have generally been carried out in a piecemeal manner, as basic research was done before the ECOHAB program. For example, after the 1997 outbreak of Pfiesteria in Maryland and Virginia, the administration created an ad hoc interagency task force to assist the states in preventing, mitigating, and controlling *Pfiesteria.* Similar efforts for other harmful algal species, however, have not been established, and, in September 1998, the Senate Committee on Commerce, Science, and Transportation reported that little had been done at the federal level to prevent and control harmful algae given the scope and seriousness of the problem.

What is the Future for a U.S. Interagency HAB Program?

The following is excerpted from a NOAA report.[98]

Although a summary of current activities suggests that the United States has a strong and active national HAB program, the program is just beginning. Commitment to multi-agency coordination of HAB activities by individual agencies has occurred only during the last five years, after each realized that no single agency possessed either the funds or expertise to respond to the suite of HAB needs. The initial partnerships among NOAA line offices for publication of the National Plan have since expanded to 3-agency sponsorship of ECOHAB research projects, then 7 agencies helped draft the National Strategy in response to the recent *Pfiesteria* crisis. With such interagency commitment, an integrated, interagency Algal Bloom Program may become a reality in the near future.

With the goal of developing a predictive modeling capability for HABs in all US coastal waters (i.e., HAB predictions like coastal weather forecasts), ECOHAB research must rigorously investigate and then model growth and toxin dynamics of the 7-8 toxic species and regions along the entire US coast. Five-year ECOHAB research projects have just begun on three toxic species and regions, *Alexandrium* in the Gulf of Maine, *Pfiesteria* in mid- and south Atlantic states, and *Gymnodinium* in the Gulf of Mexico. The remainder of the coastline and other HAB species need investigation. Research is needed on brown tide populations in Long Island Sound and off Texas, macroalgal blooms in Florida's and Hawaii's coral reefs, ciguatera dinoflagellates in sub-tropical and tropical US possessions, *Pseudo-nitzschia* in the northwestern Gulf of Mexico and along the west coast, and *Chaetoceros* and *Heterosigma* in the northwest. These efforts will be the focus of future ECOHAB research activities.

A critical area in need of major support that was identified in the National Plan and the recent National Strategy for *Pfiesteria* is better understanding of toxin impacts, both acute and chronic, on coastal resources and humans. This includes identification of the toxins and toxic cells in water and tissues; development of rapid, reliable, and inexpensive assays for their field detection; identification of biomarkers for monitoring HAB toxins in wildlife and humans; and establishment of exposure thresholds for toxicity. Additionally, development of the medical expertise specific to toxins, toxicology, and treatment should be addressed. Although some of this effort is already underway at the NIEHS Centers for research, the CDCP, a USGS laboratory, an FDA laboratory, and two NOAA laboratories, an expanded intra- and extramural program is needed to gain baseline information quickly on such complex topics.

Reducing HAB impacts is a major emphasis for the emerging national HAB program. The National Plan objective to pursue prevention, control, and mitigation options for our increasing HAB problem is a critical need. As HABs continue to increase, we must refocus our goals and research expertise toward developing techniques for detecting and ameliorating the impacts of these natural disasters.

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APPENDIX A. FEDERAL EFFORTS TO ADDRESS HABS

The following is excerpted from a General Accounting Office report.[99]

Coordinated Federal Efforts

Coordinated Federal Efforts Are Being Undertaken. Coordinated federal efforts to protect the public from harmful algae started in 1992 with a workshop sponsored by the National Oceanic and Atmospheric Administration. This workshop led to the 1993 publication of a report entitled *Marine Biotoxins and Harmful Algae: A National Plan.* Prior to 1992, federal efforts were generally restricted to responding on a case-by-case basis to new outbreaks of harmful algae. The national plan set in place an ongoing interagency process for addressing the objectives set out in the plan and resulted, in 1996, in the creation of the interagency Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) program. While the objectives in the national plan (see below) are still current, funding limitations have delayed the start of many of the projects addressing the objectives. For example, the ECOHAB program began funding several large regional projects in 1997. At the same time, however, the outbreaks of *Pfiesteria* in Maryland during the summer of 1997 tended to focus national attention on the need to take action against harmful algae, and, as a result, additional projects were funded in 1998. Because most of these projects have only recently gotten under way and have multi-year time frames, significant progress in protecting the public from harmful algae is still many years away.

Coordinated Efforts to Learn About and Manage the Effects of Harmful Algae. The 1992 NOAA-sponsored workshop brought scientists and regulatory officials together to address the problems of harmful algae. This workshop resulted in the 1993 publication of a national plan—*Marine Biotoxins and Harmful Algae: A National Plan*—for conducting basic research and developing management and mitigation strategies to protect the public and the environment from problems associated with harmful algae. In the plan, representatives from federal and state government, academia, and industry stated that the US research, monitoring, and regulatory infrastructure is not adequate to meet the expanding threats from harmful algae and established the goal of effectively managing fisheries, public health, and ecosystem problems. According to the plan, the following eight specific research objectives must be addressed to comprehensively evaluate, model, and manage harmful algae and its impacts:

- Isolating algae toxins and characterizing their chemical and pharmacological actions,
- Developing tests to identify individual toxins based on their unique chemistry,

- Developing the capability to predict the occurrence and assess the impacts of harmful algae,
- Determining the source and consequences of algae toxins in the marine food web,
- Developing management and mitigation strategies to minimize the impacts of harmful algae,
- Identifying and improving access to databases on toxic algae occurrences and impacts,
- Developing programs to communicate educa tional and public health information, and
- Providing rapid response programs for harmful algae outbreaks.

The national plan set in place an interagency process for addressing these objectives. A December 1995 report—*The Ecology and Oceanography of Harmful Algal Blooms: A National Research Agenda*—serves as a blueprint for carrying out the federal research program on the ecology and oceanography of harmful algae. This report resulted in the establishment of the ECOHAB program, the first federally coordinated effort dedicated to conducting the basic research necessary to understand the nature of harmful algae, the reasons they occur, and the steps that can be taken to control them. Under the auspices of the ECOHAB program, five federal agencies—NOAA, the Environmental Protection Agency (EPA), the National Science Foundation (NSF), the Office of Naval Research (ONR), and the National Aeronautics and Space Administration (NASA)—have funded research projects that are carried out in-house or by universities and other organizations. Other agencies, including the Centers for Disease Control and Prevention (CDC), the National Institute of Environmental Health Sciences (NIEHS), and the Food and Drug Administration (FDA), are involved in conducting research and disseminating information to the public on harmful algae. Research supported by CDC and NIEHS primarily focuses on the human health effects that result from exposure to water or aerosols containing harmful algae, while FDA's research focuses on the human health effects from exposure to toxins from consuming seafood. Collectively, these agencies spent more than $40 million in 1997 and 1998 on these efforts.

Before the ECOHAB program, research on the effects of harmful algae was typically isolated and uncoordinated. Often, the research was carried out by individual scientists and was not sustained over time. Before the program, there was essentially no overall federal coordination of the work to ensure that important national priorities were being addressed. A second report was issued in February 1997. Developed on the basis of the objectives in the national plan—*Harmful Algal Blooms in Coastal Waters: Options for Prevention, Control and Mitigation*—describes the processes and mechanisms that need to be employed to control harmful algae and their impacts. According to NOAA officials, this report is the basis for new initiatives for intervention strategies to deal with harmful algae to minimize human health, ecological, and economic impacts. *The National Harmful Algal Bloom Research and Monitoring Strategy,* published in November 1997, presents a national strategy for federally-supported research and monitoring for problems associated with harmful algae, particularly *Pfiesteria* and *Pfiesteria*-like organisms. The report is intended to serve as an action plan for *Pfiesteria* research and monitoring within the framework of the broader objectives identified in the national plan. In November 1998, NOAA published *The Status of U.S. Harmful Algal Blooms: Progress Towards a National Program*, which described a number of interagency programs designed to understand and ameliorate the impacts of harmful algae without attempting to provide a quantitative assessment of progress.

National Oceanic and Atmospheric Administration (NOAA)

National Centers for Coastal Ocean Science (NCCOS). NCCOS has established expertise and programs that focus on harmful algal blooms (HABs). NCCOS' HAB activities include research, monitoring and assessment, and event response components. Several research focus areas are proposed for both intramural and extramural programs, including factors controlling bloom growth, toxin structure and function, factors causing toxicity, detection of HABs using new technology, acute and chronic effects of HAB exposure in humans and living marine resources, paleoecological analysis of core material, remote sensing of HABs, methods of HAB mitigation and control, HAB interactions with other species, interactions between HABs and other stressors in the environment and the isolation, culture and distribution of HAB species. An intensive modeling effort is also proposed to examine linkages between the ecology, physiology, toxicity, and behavior of the HAB species, their planktonic and pelagic neighbors, their chemical environment, and physical movements of particles and water. The models develop through this activity will be transferrable between different physical environments and bloom species. These research and modeling foci will draw upon NCCOS' recognized expertise in marine biotoxins and fish lesion characterization, HAB ecology, photobiology, physical transport mechanisms and remote sensing as well as involve other agencies, States and academia in new partnerships to address some of these issues.

NCCOS is also developing an intensive monitoring program that focuses on the environmental conditions believed to be conducive to occurrences of HABs. Small teams of Federal, State, and academic experts will coordinate the planning, implementation and analytical phases of the monitoring studies. Where appropriate, these studies will incorporate emerging monitoring methods and technologies such as remote sensing to encourage their development and to provide opportunities for field testing. NCCOS will also work toward the development of a National Registry of HAB events. This Registry will be implemented online with a simple web page reporting mechanism and download system that can be easily utilized by researchers and resource managers. Retrospective analyses of existing databases will also be carried out to identify the magnitude and duration of the US HAB problems through time and possible linkages with anthropogenic activities in coastal waters. Results from these analyses will be used to develop and further refine research hypotheses.

NCCOS developed the *Federal Event Response Plan for Harmful Algal Blooms* with the Environmental Protection Agency and other Federal agencies. NCCOS is responsible for coordinating with EPA all Federal HAB event response efforts initiated under the plan. NCCOS has also identified existing internal scientific and technical capabilities that can be mobilized to support State efforts to respond to HABs and other unusual biological events.

National Marine Fisheries, Northwest Fisheries Science Center. Northwest Fisheries Science Center (NWFSC) Biotoxin Program focuses on and integrates methodology, food web interactions, species susceptibility and coastal ecosystem health. Recent highlights include development of new receptor binding and DNA probes for toxin and toxic algae detection, studies of toxin transfer through the food web, and culture studies to determine effects of nutrients on toxin production.

The NWFSC's Biotoxin Program has formed several productive research and monitoring partnerships with federal, state, and private institutions. The NWFSC Biotoxin program and the Olympic Coast National Marine Sanctuary (OCNMS) have an ongoing partnership to study offshore and inshore HAB events within in Sanctuary. The NWFSC Biotoxin program has also established a partnership with the Quileute Tribe whose lands abut the Sanctuary. This project includes researching , monitoring, and assessing the severity and spatial distribution of domoic acid in both shellfish and local waters where the tribe has its "Usual and Accustomed" fisheries. This pilot project is a model for creating partnerships between Indian Tribes, other coastal communities, federal agencies, and scientific research institutions. Plans are underway to expand this project to include other tribes along the northern coast of Washington State.

Sea Grant. With its role in marine research, education, advisory services and public outreach, Sea Grant expertise and its network of local experts plays a major role during HAB events. Sea Grant has long supported individual investigators studying local HAB problems (e.g., research first identifying *Pfiesteria* in North Carolina) and this support has built the foundation for several of the large regional HAB field projects. A series of articles recently published by Maryland Sea Grant (e.g., *In Harm's Way? The Threat of Toxic Algae*; *Harmful Algal Blooms on the Move*; and *The Trouble with Toxics in the Bay*) explained to readers the latest information on algal blooms, particularly those in the

Chesapeake Bay region and the role of the complex of *Pfiesteria*-like organisms in fish mortalities in the Pocomoke River. Sea Grant programs in Maine, Massachusetts, New York, Florida, Texas, Washington, North Carolina, and Alaska have released similar materials on HABs from those areas of the country. In 1999, the National Sea Grant Program contributed funds to ECOHAB to support research on prevention, control, and mitigation of HAB impacts on commericially important fisheries, mariculture, and public health.

Environmental Protection Agency (EPA)

EPA's Office of Water and Office of Research and Development are working to support State rapid response and monitoring activities, HAB research, and public outreach. The Office of Water (OW) is supporting efforts in State governments to establish and maintain rapid response and monitoring programs for toxic *Pfiesteria* outbreaks. EPA is supporting eleven State programs in various stages of program development, six of these States received seed funds to establish rapid response and monitoring programs in FY 1999. Additionally, OW is supporting a pilot monitoring project in the Neuse River estuary which will provide information on the role nutrient pollution in toxic *Pfiesteria* outbreaks. OW is also working with the academic community, States and our Federal partners to produce public fact sheets on HABs. Two fact sheets will address toxic *Pfiesteria* and fish lesions associated with Pfiesteria. Two additional fact sheets will deal with ciguatera fish poisoning and marine biotoxins from HABs in shellfish. The EPA Regions and OW have conducted national conferences on *Pfiesteria* that have served as forums for information exchange among State and Federal resource managers and the academic community. Other methods of information exchange include a web-site and monthly conference calls with States, other Federal agencies and academics conducted by the EPA Chesapeake Bay Program.

The Office of Research and Development (ORD) is supporting research to identify the effects of Pfiesteria and other HABs on the fresh water and marine environment through a multi-investigator research program supported and conducted at the Gulf Ecology Division (GED) in Gulf Breeze, Florida. GED research concentrates on Gulf of Mexico HABs, largely *Gymnodinium breve.* The focus of the research includes:

- Determine the critical environmental and genetic factors regulating population growth, life cycle transitions, and toxin production of HAB species,
- Determine the effects of HAB toxins on water quality, higher trophic level species, and ecosystem condition,
- Develop and implement a real-time coastal ecosystem monitoring system with early warning capabilities for HABs,
- Investigate and evaluate potential strategies to control, mitigate, and/or prevent HABs in coastal ecosystems, and
- Develop and implement a national coastal mortality monitoring network to investigate and report coastal mortalities and their most likely cause(s), including the occurrence of harmful algal blooms.

Pfiesteria piscicida has not been reported in the Gulf of Mexico to date. However, GED is developing methodologies, based on electron microscopy, to identify *Pfiesteria*-like species and other potential HABs in the marine and estuarine environment.

An Interagency Agreement has been approved between EPA/GED and NOAA/NOS/Charleston Laboratory to coordinate research on causes and impacts of marine HABs. A broader Memorandum of Understanding is being developed. A Memorandum of Understanding has been approved between EPA/GED and the US Geological Survey/Columbia Laboratory that includes coordinating research on HABs, particularly freshwater cyanobacteria

The EPA Advanced Measurement Initiative, Application of the SeaWiFS for Coastal Monitoring of Harmful Algal Blooms, seeks to identify unique spectral absorption, scattering, and reflectance properties of the red tide organism *Gymnodinium breve*, which can be applied to the SeaWiFS ocean color satellite sensor, thus allowing for the remote sensing of these organisms from space.

Specific EPA-sponsored research projects include

ECOHAB: Control of Harmful Algal Blooms Using Clay; ECOHAB: Florida, a multi-agency/investigator project that addresses HAB in Florida; and the Environmental Consequences of the Use of Veterinary Pharmaceuticals in Concentrated Animal Feedlot Operations which will investigate the relationship between these operations and HABs. Finally, the US Office of Coastal Global Ocean Observation Systems and LABNET have approved a pilot project on HAB monitoring in the Gulf of Mexico. This project will be coordinated through a partnership with EPA/GED, NOAA/NODC and NASA.

Food and Drug Administration (FDA)

FDA's ongoing marine biotoxin research program continues to progress in characterizing the various seafood toxins, developing methods for detecting them, and culturing the organisms that produce them. The FDA also routinely supplies reference standards of saxitoxin and domoic acid to other laboratories for regulatory and research purposes.

A major function of the FDA's research program is to provide technical support to state and other regulatory agencies when there are management questions or HAB outbreaks. For example, FDA provided technical support in working out a management strategy regarding giant clams (geoducks) in Washington State, and in dealing with an outbreak of PSP due to shellfish from Burley Lagoon, in southern Puget Sound in October of 1998. The latter case involved three mild illnesses from eating mussels that had been harvested and sold in a local market.

Over the past two years the FDA's research labs have investigated five outbreaks of ciguatera, all in the continental US. One of these, in Chicago, involved 21 victims who had eaten amberjack from South Florida.

The FDA, the states, and the shellfish industry continue to work together, through the structure of the Interstate Shellfish Sanitation Conference (ISSC), to ensure the safety of bivalve molluscs. Components of the FDA contributing to this effort include research laboratories, regional shellfish specialists that maintain close ties with each producing state, the Shellfish Program Implementation Branch which provides overall coordination and technical standardization, and the Office of Seafood, which provides policy guidance. The ISSC and its regional components (such as New England and Pacific Rim) also hold annual meetings.

With assistance from FDA, the Signal Environmental And Plankton Observations in Real Time (SEAPORT) networks of citizen volunteer observers are well established in California, Maine, and Massachusetts and are being developed in Connecticut, Rhode Island, and New Hampshire. The FDA encourages their development in other coastal states that have HAB problems, particularly Alaska, Washington, and Oregon. The FDA assists the states with technical support and in conducting training and refresher workshops for the volunteer observers. In addition to providing advance warning of toxicity outbreaks, these networks are accumulating an important and unprecedented body of baseline data on plankton populations along our coasts.

The FDA is a participant in the Gulf of Mexico program and, from the FDA research laboratory in Dauphin Island, Alabama, continues to provide direct lab support of marine biotoxin management programs in the Gulf coast states.

US Department of Agriculture (USDA)

USDA recognizes the strong linkages between land-use, nutrient loads, and watershed conditions. Agencies within the department are striving to keep pollutant loading, such as nutrients out of watersheds and coastal waters through research, implementation of management programs, and working with landowners/users to encourage incorporation of conservation practices into their farming operations.

USDA Agricultural Research Service (ARS) researchers are investigating the environmental effects of farming. Scientists from various disciplines are engaged in evaluating a wide range of agricultural activities including pathogen research on Crytosporidium and Pfiesteria, livestock feed efficiencies, animal waste management, ammonia source and delivery, sustainable agricultural, composting wastes, erosion control etc.

The USDA Natural Resources Conservation Service (NRCS) helps farmers reduce erosion and nutrient loading to the environment and assists locally-led conservation initiatives. NRCS provides guidance and technical expertise to help local groups tackle community resource concerns. Tools include natural resource inventories, soil surveys, conservation practice specifications, funding, and a comprehensive knowledge of resources conservation.

The agency, as an active participant in the President's Clean Water Action Plan agreed to increase technical and financial assistance to reduce polluted runoff and enhance natural resources. NRCS utilizes authorities provided through the 1996 Farm Bill offering a wide range of conservation options that can be tailored to fit special situations. Some important programs offered by NRCS include the Environmental Quality Incentives Program (EQIP) which targets assistance to high priority areas, Wetland Reserve Program (WRP) offering 30 year easements or restoration cost-share agreements, Conservation Reserve Program (CRP) allowing landowners to take environmentally sensitive areas out of production, and Wildlife Habitat Incentives Program (WHIP) allowing landowners to improve habitat for wildlife.